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Theoretical Optimization of a Water-Augmented Turbofan Marine Propulsion System

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THEORETICAL OPTIMIZATION OF A WATER-AUGMENTED TURBOFAN MARINE PROPULSION SYSTEM

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by

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ABSTRACT

This paper presents a theoretical investigation of a water-augmented turbofan engine, one in which large quantities of sea water are injected into the fan duct section. Results indicate that up to three or four times dry thrust and propulsive efficiency are obtained depending on vessel speed, fan pressure ratio, and amount of water injected. Optimum water injection velocity is investigated. Deviations from thermal and dynamic equilibrium in the mixing processes are investigated with respect to their effect on overall performance.

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NOMENCLATURE

SYMBOL	MEANING
a	Sound speed (ft/sec)
A	Area (ft^2)
BR	Bypass ratio
Cp	Specific heat at constant pressure (ft-lb/slug-^oR)
FAR	Fuel-air ratio
g	Acceleration of gravity (ft/sec^2)
H	Enthalpy (ft-lb/slug)
HVF	Lower heating value of fuel (BTU/lbm)
J	Joules constant (778 BTU/ft-lb)
M	Mach number
MR	Mixture ratio
MW	Molecular weight
m	Mass flow rate (slug/sec)
P	Pressure (lb/ft^2)
PP	Partial pressure (lb/ft^2), (atm)
R	Gas constant (ft-lb/slug-^oR)
S	Entropy (ft-lb/slug-^oR)
SFC	Specific fuel consumption (lb_{fu}/lb-hr)
ST	Specific thrust $\frac{(lb_f\text{-sec})}{lb_m}$
T	Temperature (^oR)
TH	Thrust (lb)

SYMBOL	MEANING
V	Velocity (ft/sec)
$\overline{V}$	Mean velocity (ft/sec)
WGR	Water to gas generator air ratio
X	Specific humidity
γ	Ratio of specific heats
η	Efficiency
ρ	Density (slug/ft^3)

SUBSCRIPT	MEANING
A	Air
B	Burner
C	Compressor
D	Gas generator diffusor
f	Saturated liquid
fg	Change by evaporation
fu	Fuel
F	Fan
FD	Fan diffusor
g	Saturated vapor
i	Refers to property at station (i), i = 1,2...
I	Refers to state reached by isentropic process
N	Gas generator nozzle
P	Propulsive
REFA	Reference of air

SUBSCRIPT	MEANING
S	Static
T	Total, Turbine
W	Water
V	Vapor

CHAPTER I

INTRODUCTION

With the present day emphasis on nuclear propulsion and its far reaching effects on a modern Navy, advances in other types of marine propulsion may appear less necessary and certainly less glamorous. However, the significance of small to medium displacement craft in a limited conflict has been forcibly brought home by the role such craft are playing in Vietnam and in other troubled and far-reaching corners of the globe. One of the major features of the limited conflict is the speed and mobility of participating units, generally with respect to land and air forces; however, naval forces must soon follow with faster vessels. With existing types of propulsion, speed increases must be paid for with dramatic weight increases often outweighing the speed increase. Consequently, one of the most recent fields of endeavor in marine propulsion has been to develop a system that supplies enough power to attain high speeds and yet is lightweight by comparison. This paper deals with one of the most recent proposals, the water-augmented turbofan engine.

Gas turbines are currently being used to drive conventional screw propeller vessels and more exotic systems such as the water-jet driven hydrofoil (PCH-2) of the U. S. Navy. However, little serious thought has been given to using turbines for jet propulsive power since the high exit velocities inherent in gas turbines (even in turbofan engines)

produce characteristically low propulsive efficiency and are thus too impractical. Conventional thrust augmentation by water injection was considered; however, this generally involved injection of water into the compressor air flow or into hot turbine exhaust gases. In the case of the former, high purity water would be necessary because of the contact with vital moving parts. In both cases the high temperatures of the gas generator would vaporize most of the water, and the energy required to accomplish this would negate the thrust increases (1). A mixed flow turbofan where fan duct and gas generator exhaust through the same nozzle would have the same deficiency since high temperatures in the combined nozzle would again vaporize most of the water. Davison and Sadowski (2) proposed a novel method of injecting sea water into the relatively cool flow of a fan duct where the fan and gas generator exhaust through separate nozzles. As a consequence, very little water is vaporized, and no moving parts are contacted, making the use of sea-water feasible. See Figure 1.

The purpose of this paper is to optimize the design point parameters of bypass ratio, water to gas generator ratio, and those velocity, temperature, and pressure ratios that directly affect the performance of this system with respect to specific thrust and propulsive efficiency. In particular, it is desired to determine to what extent departures from thermodynamic and dynamic equilibrium in the mixing processes affect performance and what critical limits exist, if any. It would then have to be established experimentally that a mixing duct with two-phase flow in the actual conditions would satisfy these requirements.

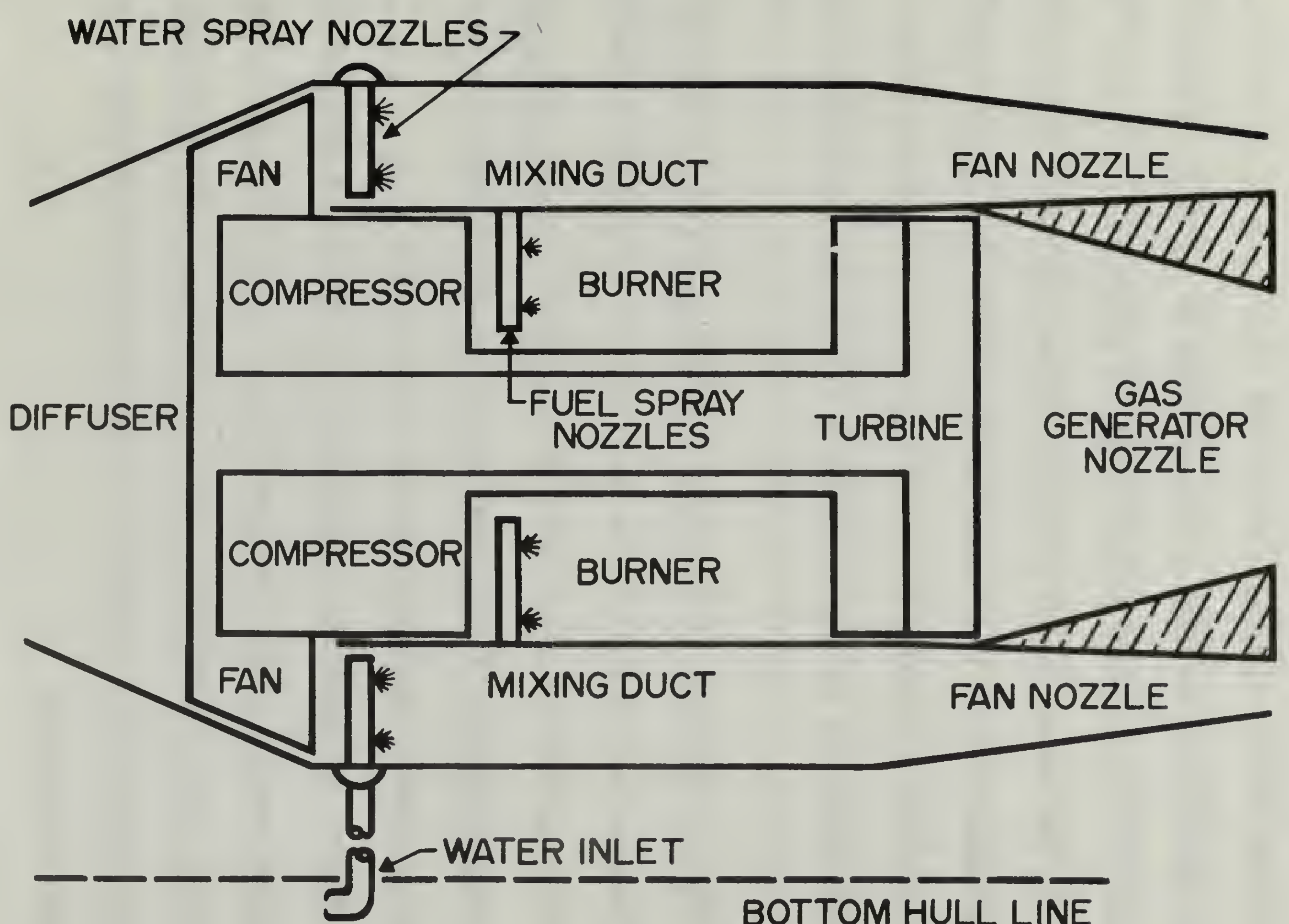


FIGURE 1
WATER-AUGMENTED TURBOFAN ENGINE (ACTUAL)

This is both necessary and important for two reasons. First, the work of Davison and Sadowski (2), which constitutes the only major effort on the subject, deals with one particular engine and one fixed set of operational parameters. In other words, they have shown it to be feasible for one particular engine but have made no effort to find under what conditions such a system would be optimum, and such information is necessary for the design of a prototype. Second, an experimental mixing duct/fan nozzle section should be constructed to experimentally verify the theoretical findings of this paper, especially with regard to acceptable limits for velocity and temperature lags between water and air and also mixing duct lengths necessary to achieve them.

The data obtained in the paper were obtained from a computer program designed to analyze the performance of the water-augmented turbofan engine while parametrically varying the critical design parameters so that graphical and tabular displays of thrust and efficiency variation could be obtained and optimum points determined.

Briefly, the remainder of the thesis will present a description of the model used, develop the equations upon which the computer program is based, present methods of analyzing the data, and conclude with results, discussion, conclusions, and suggestions for further work to be done in this area.

CHAPTER II

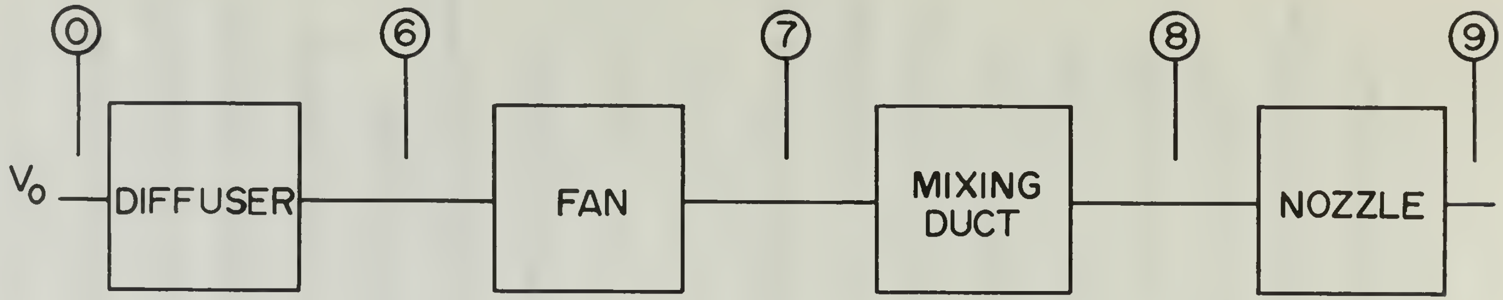
DESCRIPTION OF MODEL USED

2.1 Physical Layout

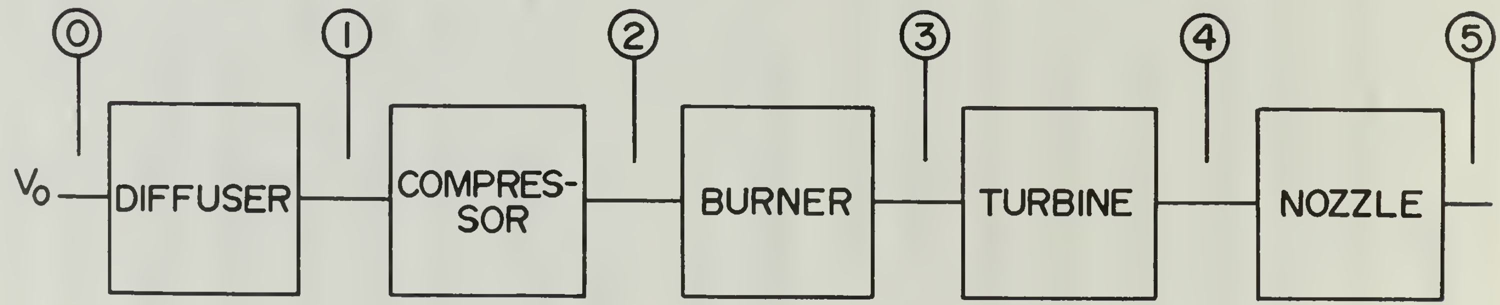
Figure 2 is a block-schematic diagram of the operating system depicted in Figure 1. Important points to consider are that the fan duct system is completely separate from the gas generator system with separate exhausts and that water injection occurs in the mixing duct entrance after the fan, thus contacting no moving parts. All stations are numbered in Figure 2; and when a numerical subscript is involved in an equation, the quantity thus subscripted is measured at that station in the engine. It should be noted that the figures do not show fuel tanks, water injection pumping systems, or any other components contained in the actual engine.

2.2 Assumptions

Because of the large number of variables in an analysis of this type, many simplifying assumptions had to be made to limit computational time. The air was assumed to be behaving as a perfect gas with constant specific heats. As is common practice in rough design work in turbomachinery applications, Cp was assumed constant at one value for low temperatures and constant at a second value for high temperatures. Gamma was then computed from the appropriate value of Cp. For the purposes of this investigation, a plot of Cp versus temperature of the gas was made from data in reference (3). The results of this were two



FAN SECTION



GAS GENERATOR

FIGURE 2

WATER-AUGMENTED TURBOFAN ENGINE (BLOCK)

values for Cp for the two temperature conditions. For the combustion chamber, which is the transition between the two extremes, an arithmetic mean of the two values of Cp was used. This was justified on the basis that the plot of Cp versus temperature was roughly a straight line in the region of interest. Viscous effects were ignored with the exception of the influence of the water on the air in the fan duct. It was assumed that no heat was transferred other than in the combustion chamber, and no work was transferred other than in the turbine, compressor, and fan. Mixing duct area was assumed constant, and it was also assumed that the engine would have only converging nozzles. In other words, both gas generator and fan exit at atmospheric pressure; however, if this produced an exit Mach number greater than one, the values were recomputed to exit at a higher pressure with sonic velocity. The last major assumption made in the initial analysis was that the air entering the system was dry air with no relative humidity effects. For ease in calculations one slug of air was assumed to be entering the gas generator per unit time. As a consequence, bypass ratio was also the mass flow through the fan section per unit time, and an increase in bypass ratio keeping other parameters constant was an increase in fan section size holding gas generator size constant.

CHAPTER III

ANALYSIS OF DRY TURBOFAN

With zero water injection, the analysis of the system is developed from H-S diagram relationships and basic equations of engineering science. This chapter and the equations contained in it are arranged in sections similar to those contained in the computer program for the dry turbofan engine.

3.1 Gas Generator Diffuser

Ambient total pressure is determined from

$$P_{TO} = P_{SO}\left(1 + \frac{\gamma - 1}{2} M_O^2\right)^{\frac{\gamma}{\gamma-1}} \tag{1}$$

so that defining diffuser efficiency as

$$\eta_D = \frac{P_{T1} - P_{SO}}{P_{TO} - P_{SO}} \tag{2}$$

it follows that

$$P_{T1} = P_{SO} + \eta_D\left(P_{TO} - P_{SO}\right) \tag{3}$$

Since no work is done in the diffuser,

$$T_{T1} = T_{TO} = T_{SO}\left(1 + \frac{\gamma - 1}{2} M_O^2\right) \tag{4}$$

and enthalpy is

$$H_{T1} = C_{PC}\left(T_{T1} - T_{SO}\right) + H_{REFA} \tag{5}$$

where H_{REFA} is the enthalpy of the air at T_{SO}.

3.2 Compressor

The ideal (isentropic) temperature at compressor exit for a specified pressure ratio $\frac{P_{T2}}{P_{T1}}$ is

$$T_{T2I} = T_{T1}\left(\frac{P_{T2}}{P_{T1}}\right)^{\frac{\gamma-1}{\gamma}} \tag{6}$$

Define compressor efficiency as the ratio of isentropic work input to actual work input; thus

$$H_{T2} = \frac{C_{PC}\left(T_{T2I} - T_{T1}\right)}{\eta_c} + H_{T1} \tag{7}$$

$$T_{T2} = \frac{\left(H_{T2} - H_{REFA}\right)}{C_{PC}} + T_{SO} \tag{8}$$

3.3 Combustor (Burner)

Recall from Section 2.2 $\quad C_{PB} = \frac{\left(C_{PC} + C_{PH}\right)}{2.0}$

T_{T3} is fixed by maximum allowable turbine inlet temperature.

Therefore

$$H_{T3} = C_{PB}\left(T_{T3} - T_{T2}\right) + H_{T2} \tag{9}$$

Writing the energy equation across the burner,

$$\dot{m}_c H_{T2} + \dot{m}_{fu}\left(H_{fu2} + \eta_B HVF\right) = \left(\dot{m}_c + \dot{m}_{fu}\right) H_{T3}$$

If it is assumed that injection temperature of the fuel is equal to air temperature at that point, and the energy needed to vaporize the fuel is included by choosing the lower heating value of the fuel, then

$$FAR = \frac{C_{P_H}\left(T_{T3} - T_{T2}\right)}{\eta_B \cdot HVF \cdot g \cdot J - C_{P_H}\left(T_{T3} - T_{T2}\right)} \tag{10}$$

3.4 Turbine

For the entire system work input must equal work output; therefore, H_{T4} may be calculated from

$$\dot{m}_T\left(H_{T4} - H_{T3}\right) = \dot{m}_C\left(H_{T2} - H_{T1}\right) + \dot{m}_F\left(H_{T7} - H_{T6}\right) \tag{11}$$

and

$$T_{T4} = T_{T3} - \frac{\left(H_{T3} - H_{T4}\right)}{C_{P_H}} \tag{12}$$

Turbine efficiency is the ratio of actual work output to isentropic work output, so that

$$T_{T4I} = T_{T3} - \frac{\left(H_{T3} - H_{T4}\right)}{\eta_T\, C_{P_H}} \tag{13}$$

An expansion whether isentropic or actual is to the same pressure; therefore,

$$P_{T4} = P_{T4I} = P_{T3}\left(\frac{T_{T4I}}{T_{T3}}\right)^{\frac{\gamma}{\gamma-1}} \tag{14}$$

3.5 Gas Generator Nozzle

Since no work is done in the nozzle,

$$T_{T4} = T_{T5}$$

Knowing that the flow exits to ambient pressure fixes the pressure ratio $\frac{P_{S5}}{P_{T4}}$.

Thus

$$T_{S5I} = T_{T4}\left(\frac{P_{S5}}{P_{T4}}\right)^{\frac{\gamma-1}{\gamma}}. \tag{15}$$

Define a nozzle efficiency

$$\eta_N = \frac{T_{T4} - T_{S5}}{T_{T4} - T_{S5I}} \tag{16}$$

Equation (16) may be solved for T_{S9} and exhaust velocity determined from

$$V_{A5} = \sqrt{2 \cdot C_{P_C} \left(T_{T5} - T_{S5} \right)} \tag{17}$$

Sound speed is

$$a_5 = \sqrt{\gamma_H R T_{S5}}$$

Therefore exit Mach number

$$M_5 = \frac{V_{A5}}{a_5} \tag{18}$$

Note the comments in Section 2.2 concerning procedure when $M_5 > 1$

3.6 Fan Diffuser

Specifying a separate fan diffuser efficiency η_{FD}, the equations for the fan diffuser correspond to equations (2) through (5) with subscript 6 substituted for subscript 1.

3.7 Fan

With a corresponding fan pressure ratio $\frac{P_{T7}}{P_{T6}}$ and fan efficiency, η_F, the fan equations are identical to the compressor equations of Section 3.2 with the subscripts 7 and 6 substituted for the subscripts 2 and 1 respectively.

3.8 Fan Mixing Duct

No work is done in the mixing; therefore,

$$T_{T7} = T_{T8} \tag{19}$$

$$P_{T8} = \left(\frac{P_{T8}}{P_{T7}} \right) P_{T7} \tag{20}$$

3.9 Fan Nozzle

The equations of Section 3.5 are valid for the fan nozzle also with subscripts 9 and 8 substituted for 5 and 4 respectively and the proper fan nozzle efficiency specified. It should be noted at this point that the entropy at all stations is calculated from relationships similar to

$$S_{Ti} = C_{Pc} \ln\left(\frac{T_{Ti}}{T_{SO}} \right) - R \ln\left(\frac{P_{Ti}}{P_{SO}} \right) + S_{REFA} \tag{21}$$

where S_{refa} is the entropy at T_{SO} and P_{SO}.

3.10 Specific Thrust, Propulsive Efficiency, and Specific Fuel Consumption

Thrust is determined from the momentum flux equation

$$TH = \dot{m}_T V_{A5} - \dot{m}_C V_0 + \dot{m}_F (V_{A9} - V_0) + A_5 (P_{S5} - P_{S0}) \tag{22}$$

Specific thrust based on the total mass flow of air entering the system is

$$ST = \frac{TH}{g(\dot{m}_C + \dot{m}_F)} \tag{23}$$

Propulsive efficiency is a measure of how well the system is converting the change in kinetic energy of the working medium into thrust power of the vehicle and can be shown to be

$$\eta_P = \frac{|TH \cdot V_0|}{|TH \cdot V_0| + \dot{m}_T \left|\frac{V_{A5} - V_0}{2}\right|^2 + \dot{m}_F \left|\frac{V_{A9} - V_0}{2}\right|^2} \tag{24}$$

Specific fuel consumption is the number of pounds of fuel required to produce one pound of thrust continuously for one hour and can be shown to be

$$SFC = \frac{FAR \cdot \dot{m}_C \cdot 3600 \cdot g}{TH} \tag{25}$$

CHAPTER IV

FIRST WATER INJECTION ANALYSIS

The injection of water in the mixing duct does not affect the results of Sections 3.1 through 3.7. The equations contained in these sections are still valid for the case of water injection. The new analysis is based on solving the problem in the mixing duct and fan nozzle and evaluating the new specific thrust and efficiency from the information.

In this first water injection analysis it was assumed that none of the water in the mixing duct and fan nozzle sections was vaporized. The rationale behind this assumption is that, according to reference (2), much less than one per cent of the water is vaporized.

4.1 Definitions

The following terms will be used throughout the chapters dealing with water injection:

Bypass Ratio (BR) $= \dot{m}_F / \dot{m}_C$

Water to Gas Generator Ratio (WGR) $= \dot{m}_W / \dot{m}_C$

Mixture Ratio (MR) $= \dot{m}_W / \dot{m}_F$

The mean velocity at a station is defined after Elliot (4) as the velocity that the air and water would attain if they were allowed to reach equilibrium at that station with no loss in momentum.

$$\dot{m}_F V_A + \dot{m}_W V_W = \left(\dot{m}_F + \dot{m}_W\right) \bar{V} \tag{26}$$

thus,

$$\text{Mean Velocity } (\bar{V}) = \frac{V_A + MR \cdot V_W}{1 + MR} \tag{27}$$

4.2 Mixing Duct

The momentum equation for the assumptions of the paper is

$$\left(\dot{m}_F + \dot{m}_W\right) d\bar{V} = -A\,dP \tag{28}$$

The area occupied by the air is $\dot{m}_F / \rho_A V_A$

The area occupied by the water is $\dot{m}_W / \rho_W V_W$

Thus, the total flow area is $A = \dot{m}_F \left(\frac{1}{\rho_A V_A} + \frac{MR}{\rho_W V_W} \right)$ (29)

Combining equations (29) and (28) and utilizing the fact that the mixing duct is assumed to be of constant area, equation (28) can easily be integrated and becomes

$$\bar{V}_8 = \bar{V}_7 + \left(P_{S7} - P_{S8}\right)\left(\frac{1}{1+MR}\right)\left(\frac{1}{\rho_A V_A} + \frac{MR}{\rho_W V_W}\right) \tag{30}$$

The energy equation is

$$\begin{aligned} \dot{m}_F\left(H_{S7} + \frac{V_{A7}^2}{2}\right) + \dot{m}_W\left(H_{W7} + \frac{V_{W7}^2}{2}\right) &= \\ \dot{m}_F\left(H_{S8} + \frac{V_{A8}^2}{2}\right) + \dot{m}_W\left(H_{W8} + \frac{V_{W8}^2}{2}\right) & \end{aligned} \tag{31}$$

Equations (30) and (31) have five unknowns: PS8, VA8, VW8, TS8, and TW8. With three equations lacking for a solution, it was necessary to specificy ratios of unknowns to serve as equations. These three remaining equations were

$$TSR8WA = TW8/TS8 \tag{32}$$

$$VR8WA = VW8/VA8 \tag{33}$$

$$PSR87 = PS8/PS7 \tag{34}$$

These admirably suited the eventual task of determining the effect of deviations from equilibrium in this mixing process on overall performance.

4.3 Fan Nozzle

The momentum equation cannot now be integrated to yield an equation of the form of equation (30) since variation of area and pressure in the nozzle is unknown. Several attempts were made to provide a second equation either from known facts or from assumptions concerning area variation in the nozzle with varying results. The problem was rendered academic when the underlying assumption of no water vaporization was found to yield erroneous results. (See Section 4.4.)

4.4 Conclusion of First Attempt

A continuity equation was introduced into the mixing duct calculations in order to reduce the number of variable ratios specified. It was introduced in the form of

$$A_7 = A_8$$

or more specifically

$$\left(\frac{\dot{m}_F}{\rho_{A7} V_{A7}} + \frac{\dot{m}_W}{\rho_{W7} V_{W7}} \right) = \left(\frac{\dot{m}_F}{\rho_{A8} V_{A8}} + \frac{\dot{m}_W}{\rho_{W8} V_{W8}} \right) \tag{35}$$

The problem was now overspecified with more equations than unknowns. When two of the three ratios in equations (32)-(34) were used with continuity, momentum, and energy as defined in equations (30), (31), and (35), ridiculous values were produced for the unknown variables. Careful analysis of the equations involved revealed that they were correct for the given assumptions indicating that the assumptions needed re-evaluation. The net result was that the assumption concerning no vaporization of the water was not correct, and, indeed, vaporization of the water was found to play a large role in determining the solution. Admittedly a very small percentage of water is vaporized, but for two reasons its effect is significant. First, the entalpy of water vapor is roughly one-thousand BTU's per lbm. greater than that of liquid water. Second, the amount of water present with respect to air (MR) is a number ranging in value from roughly ten to four hundred. Thus the contribution in an energy equation of vaporized water had to be taken into account along with the resultant change in water mass flow.

CHAPTER V

SECOND WATER INJECTION ANALYSIS

The second analysis is similar to that of Davison and Sadowski (2). However, it differs in that their work involves the assumptions of thermal and dynamic equilibrium in the mixing duct, dynamic equilibrium in the fan nozzle, and zero pressure change in the mixing duct while this paper takes into account possible variations in these quantities.

5.1 Steam Table Properties

It was necessary in the second analysis to calculate the properties of enthalpy of the liquid (Hf), enthalpy change by vaporization (Hfg), enthalpy of the saturated vapor (Hg), entropy of the liquid (Sf), entropy change by vaporization (Sfg), entropy of the saturated vapor (Sg), and partial pressure of the vapor (PPv). These are all complicated functions of temperature. A least squares method was used to fit data points read in from the steam tables (5) in the range of interest, and it was found that a cubic approximation gave accuracy down to the last significant figure in the steam tables. The exception was partial pressure of the vapor, the actual equation of which was simple enough to be included in the program directly. Since

$$H_g = H_f + H_{fg} \tag{36}$$

and

$$S_g = S_f + S_{fg} \tag{37}$$

it was necessary only to compute the properties Hf, Hfg, Sf, and Sfg, thus determining Hg and Sg. The equations generated by the four least squares approximations and the PPv calculation are

$$HF = -5.2244716\text{x}10^{2} + (1.1719422)(Tw) - (3.1882153\text{x}10^{-4})(Tw)^{2} + (1.9421466\text{x}10^{-7})(Tw)^{3} \quad (38)$$

$$HFG = 1.440548\text{x}10^{3} - (1.1017804)(Tw) + (1.0967588\text{x}10^{-3})(Tw)^{2} - (7.4163358\text{x}10^{-7})(Tw)^{3} \quad (39)$$

$$SF = -1.6947235 + (5.325\text{x}10^{-3})(Tw) - (4.7499752\text{x}10^{-6})(Tw)^{2} + (1.8842757\text{x}10^{-9})(Tw)^{3} \quad (40)$$

$$SFG = 8.812883 - (2.442480\text{x}10^{-2})(Tw) + (2.8390143\text{x}10^{-5})(Tw)^{2} - (1.2441932\text{x}10^{-8})(Tw)^{3} \quad (41)$$

Equations (38) through (41) are valid in the range of temperatures from 510 ^{O}R to 660 ^{O}R. Tw, the temperature of the liquid, is in degrees Rankine, and the units of output for the curve fit are BTU/lbm for enthalpy and BTU/lbm-^{O}R for entropy. In the equations that follow it will be assumed that Hfg, for example, has already been converted into ft-lb/slug.

$$\log_{10}(PPv) = \log_{10}(Pc) - \frac{X}{T}\left[\frac{A + BX + CX^{3}}{1 + DX}\right] \quad (42)$$

where

$Pc = 218.167$ atm.

$X = (647.27 - T)\ ^{O}K$

$T = (Tw - 492)(9/5) + 273.16\ ^{O}K$

$A = 3.2437814$

$B = 5.86826 \times 10^{-3}$

$C = 1.1702379 \times 10^{-8}$

$D = 2.1878462 \times 10^{-3}$

and the answer, PPv, will be in atmospheres. Again, in the equations that follow, it will be assumed that PPv has been converted into lb/ft^2.

5.2 Mixing Duct

The specific humidity, X, of the mixture is defined as the ratio of the mass of water vapor to the mass of dry air in the system. From perfect gas equations for dry air and water vapor, it can be shown that

$$X_8 = \left(\frac{P_{PV8}}{P_{S8} - P_{PV8}}\right)\left(\frac{MW_V}{MW_A}\right)\left(\frac{T_{S8}}{T_{V8}}\right) \tag{43}$$

It was assumed that vapor temperature was equal to liquid temperature. Taking into account vaporization, the energy equation is now

$$\dot{m}_F\left(H_{S7} + \frac{V_{A7}^2}{2}\right) + \dot{m}_{W7}\left(H_{f7} + \frac{V_{W7}^2}{2}\right) = \dot{m}_F\left(H_{S8} + \frac{V_{A8}^2}{2}\right) \tag{44}$$
$$+ \left(\dot{m}_{W7} - X_8\dot{m}_F\right)\left(H_{f8} + \frac{V_{W8}^2}{2}\right) + X_8\dot{m}_F\left(H_{g8} + \frac{V_{A8}^2}{2}\right)$$

The momentum equation (29) and its integrated result (30) are still valid for the case of vaporization. The problem is now one of three equations: (44), (43), and (30) with six unknowns: VW8, VA8, TW8, TS8, PS8, and X8. By again specifying ratios of unknowns, equations (32) through (34), a solution is possible. However, an explicit solution is

not possible since equations (43) and (44) contain involved functions of TW8 through the enthalpy and partial pressure terms. VA8 and VW8 may be solved using equations (30), (33), and (34). The remaining equations may be manipulated in such a manner as to yield a function of TS8 only (called FUN) which is equal to zero. A Newton Rhapson iterative solution may then be applied

$$TS8_j = TS8_{j-1} - FUN/DFUN \tag{45}$$

where $TS8_j$ is the j^{th} approximation, $TS8_{j-1}$ is the $(j-1)^{th}$ approximation, and DFUN is the derivative of the function with respect to TS8, both evaluated at $TS8_{j-1}$. When the correct value of TS8 is reached, FUN will equal zero, and TW8 and X8 may be calculated from equations (32) and (43).

5.3 Fan Nozzle

Along the same reasoning as in Section 5.2, specific humidity at the fan nozzle exit is

$$X_9 = \left(\frac{PPV9}{PS9 - PPV9}\right)\left(\frac{MW_V}{MW_A}\right)\left(\frac{TS9}{TV9}\right) \tag{46}$$

Note again vapor temperature was assumed equal to liquid temperature.

With varying area, the momentum equation cannot be solved unless a geometric configuration is specified. Therefore, the assumption was made that the net change in entropy through the nozzle is zero. That is

$$\left(S_9 - S_8\right)_{AIR} + \left(S_9 - S_8\right)_{WATER} = 0 \tag{47}$$

Expanding $\dot{m}_F \left[C_{Pc} \ln\left(\frac{T_{S9}}{T_{S8}}\right) - R \ln\left(\frac{P_{S9}}{P_{S8}}\right)\right] +$

$$\left[\left(\dot{m}_{W7} - X_9 \cdot \dot{m}_F\right) S_{f9} + \dot{m}_F X_9 S_{g9}\right] -$$

$$\left[\left(\dot{m}_{W7} - X_8 \dot{m}_F\right) S_{f8} + \dot{m}_F X_8 S_{g8}\right] = 0 \tag{48}$$

Since exit pressure is atmospheric, the equations (48) and (46) have TS9, TW9, and X9 unknown. By specifying

$$TSR9WA = TW9/TS9 \tag{49}$$

and solving equations (46) and (48) for a function of TS9 equal to zero, the Newton-Rhapson iterative method again yields values for TS9, TW9, and X9. The energy equation may be written

$$\dot{m}_F\left(H_{S8} + \frac{V_{A8}^2}{2}\right) + \left(\dot{m}_{W7} - X_8 \dot{m}_F\right)\left(H_{f8} + \frac{V_{W8}^2}{2}\right)$$

$$+ \dot{m}_F X_8\left(H_{g8} + \frac{V_{A8}^2}{2}\right) = \dot{m}_F\left(H_{S9} + \frac{V_{A9}^2}{2}\right) +$$

$$\left(\dot{m}_{W7} - X_9 \dot{m}_F\right)\left(H_{f9} + \frac{V_{W9}^2}{2}\right) + \dot{m}_F X_9\left(H_{g9} + \frac{V_{A9}^2}{2}\right) \tag{50}$$

Let $$VR9WA = VW9/VA9 \tag{51}$$

and solve equations (50) and (51) for VW9 and VA9

$$V_{A9} = \left\{ \frac{\left[C_{Pc}\left(T_{S8} - T_{S9}\right) + X_8 H_{fg8} - X_9 H_{fg9} + MR\left(H_{f8} - H_{f9}\right) + \frac{V_{A8}^2}{2}\left(1 + X_8 + \left(MR - X_8\right) VR8WA^2\right)\right]}{\left[1 + X_9 + \left(MR - X_9\right) VR9WA^2\right]/2} \right\} \tag{52}$$

5.4 Specific Thrust and Propulsive Efficiency

Thrust, specific thrust, and propulsive efficiency are defined as before, but account must be taken of the varying mass flow rates in the mixing sections.

$$TH = \dot{m}_T V_{A5} - \dot{m}_C V_0 + \left(\dot{m}_F + X_9 \dot{m}_F\right) V_{A9} - \dot{m}_F V_0$$

$$+ \left(\dot{m}_{W7} - X_9 \dot{m}_F\right) V_{W9} - \dot{m}_{W7} V_{W0} + A_5 \left(P_{S5} - P_{S0}\right) \quad (53)$$

$$ST = \left(\frac{1 + FAR}{1 + BR}\right) V_{A5} - \left(\frac{1}{1 + BR}\right) V_0 + \frac{\left[BR\left(1 + X_9\right)\right]}{\left(1 + BR\right)} V_{A9} - \left(\frac{BR}{1 + BR}\right) V_0$$

$$+ \left(\frac{WGR - X_9 BR}{1 + BR}\right) V_{W9} - \left(\frac{WGR}{1 + BR}\right) V_{W0} + \left(\frac{1 + FAR}{\left(1 + BR\right) \rho_{A5} V_{A5}}\right) \left(P_{S5} - P_{S0}\right) \quad (54)$$

$$\eta_P = TH \cdot V_0 \Big/ \left[\left(TH \cdot V_0\right) + \dot{m}_T \frac{\left(V_{A5} - V_0\right)^2}{2} + \right.$$

$$\left. \left(\dot{m}_F + X_9 \dot{m}_F\right) \frac{\left(V_{A9} - V_0\right)^2}{2} + \left(\dot{m}_{W7} - X_9 \dot{m}_F\right) \frac{\left(V_{W9} - V_{W0}\right)^2}{2}\right] \quad (55)$$

It should be noted that ambient air velocity was assumed equal to ambient water velocity. In other words, wind and current were neglected.

CHAPTER VI

RESULTS AND DISCUSSION

6.1 Organization of Output

The results obtained focus on two basic indicators of water-augmented turbofan performance. These are the ratio of specific thrust for the water-augmented engine to specific thrust for the dry engine and the ratio of propulsive efficiency for the wet engine to propulsive efficiency for the dry engine. Hereafter these two parameters will be referred to as thrust ratio and efficiency ratio. The final data concern two broad areas of interest, the effect of variations in general system parameters on thrust ratio and efficiency ratio holding mixing section equilibrium parameters fixed at 1.0, and the effect of variations in mixing section equilibrium parameters on thrust ratio and efficiency ratio holding all other system parameters constant.

Subsequent figures show plots of these variations and also the effect of water injection velocity on system performance.

6.2 General System Parameters vs. Thrust and Efficiency Ratios

The parameters originally thought to have the most significant effects on thrust ratio (TR) and efficiency ratio (η R) are water to gas generator air ratio (WGR), ship speed (VO), and fan pressure ratio (FPR). Performance is also improved by increasing the bypass ratio (BR), but this parameter was not thoroughly investigated since its limit is a function of design considerations only.

Figure 3 presents thrust ratio versus WGR for varying VO and FPR. The more water injected, the greater is its influence on the air as evidenced by a decrease in fan nozzle exit velocity (VA9). From the thrust equation, equation (53), it can be seen that a point is reached with increasing WGR where the negative contribution of the momentum drag of the water outweighs the positive contributions to thrust. That is, the momentum flux into the system eventually increases more rapidly than the momentum flux out. Thus, in general, the curves increase, reach a maximum or peak value, and then fall off as more water is added. Note that for a higher value of VO, values of TR are much lower. This is because of the increase in inlet momentum drag of the air and water with respect to other thrust contributions. Also note that at the higher values of VO, the curves peak at a lower WGR. Again, this is because the inlet momentum drag of the water predominates over the increase in thrust much more rapidly.

In comparing Figure 3 with the curves obtained by Davison and Sadowski (2), close correlation is found in shape and numerical values with differences attributable to the fan pressure ratio. In this paper fan pressure ratio is defined as the ratio of total pressure aft of the fan to total pressure before the fan, thus making mixing duct static pressure a variable with ship speed, while Davison apparently defines fan pressure ratio as the ratio of static pressure aft of the fan to ambient pressure, since his mixing duct static pressure is constant for all ship speeds. Figure 3 shows the fan pressure ratio to be an extremely important design

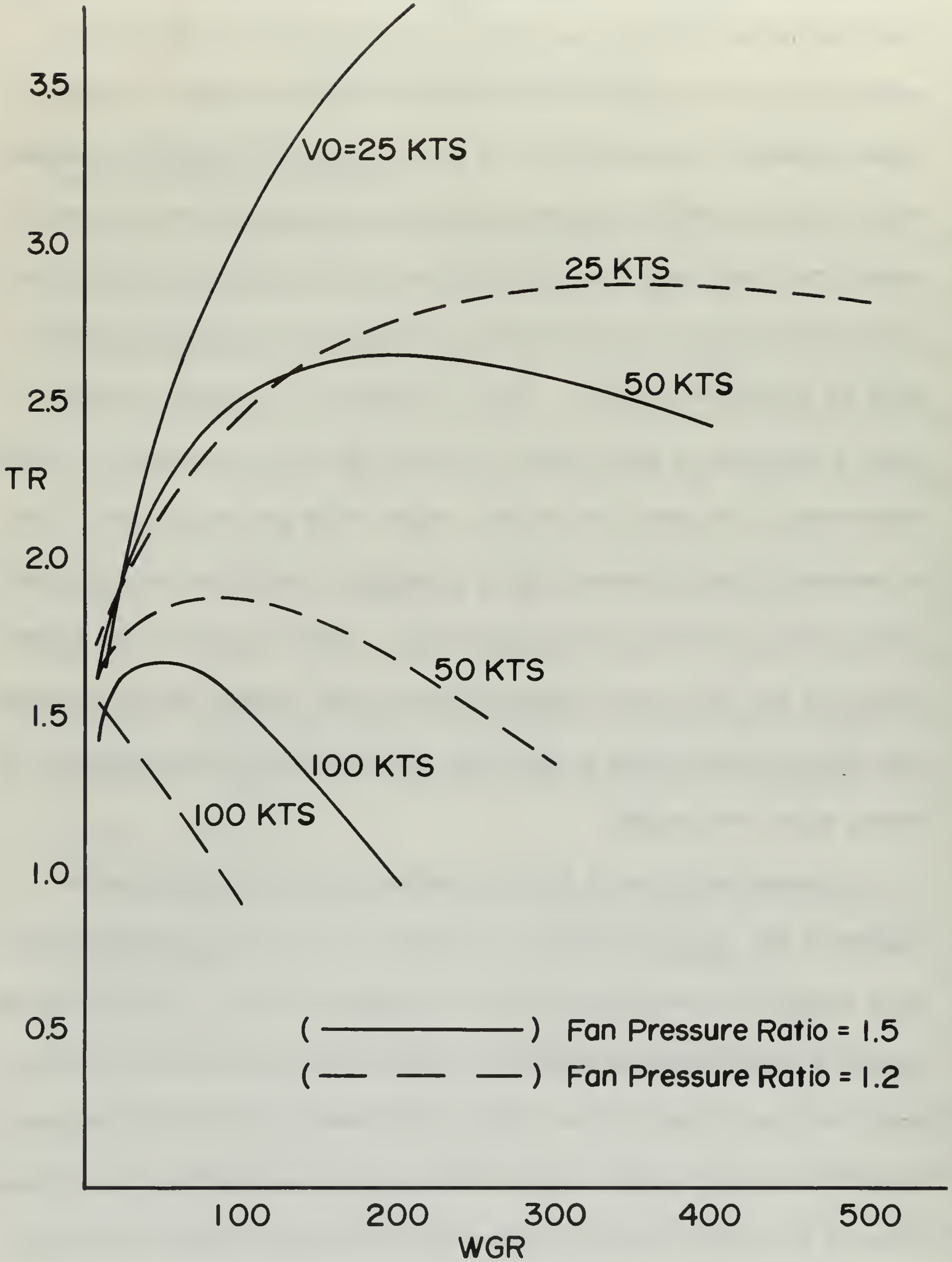


FIGURE 3

THRUST RATIO VS. WATER TO GAS GENERATOR RATIO

parameter when water injection is considered. The values of thrust ratio obtained clearly indicate that excellent values of peak thrust augmentation could be obtained in the order of upwards of three times dry thrust to over one and one-half times dry thrust.

Figure 4 presents efficiency ratio versus the same independent parameters with a constant fan pressure ratio. The shape of the curves obtained is nearly identical to those in Figure 3 with roughly similar numerical values. Efficiency ratios peak at slightly higher values of WGR than the corresponding thrust ratio indicating that efficiency ratio is slightly less sensitive to the increase in momentum drag of the water. No particular peak value predominated over the range of velocities for either thrust ratio or efficiency ratio. However, for a specified velocity and fan pressure ratio, a nearly identical value of optimum WGR was found for both thrust and efficiency ratios. Significant was the fact that at higher velocities this value was relatively low indicating that high speed craft are equally if not more suitable for water injection that those operating at lower speeds.

6.3 Equilibrium Parameters vs. Thrust and Efficiency Ratios

For the analysis of variations in mixing duct and fan nozzle equilibrium parameters on thrust and efficiency ratios, craft speed was fixed at fifty knots, fan pressure ratio at 1.5, bypass ratio at 4, WGR at 50, and compressor pressure ratio at 13.8. The four equilibrium parameters chosen were the ratio of water to air temperature at mixing duct exit (TW8/TS8) and fan nozzle exit (TW9/TS9), the ratio of water to air

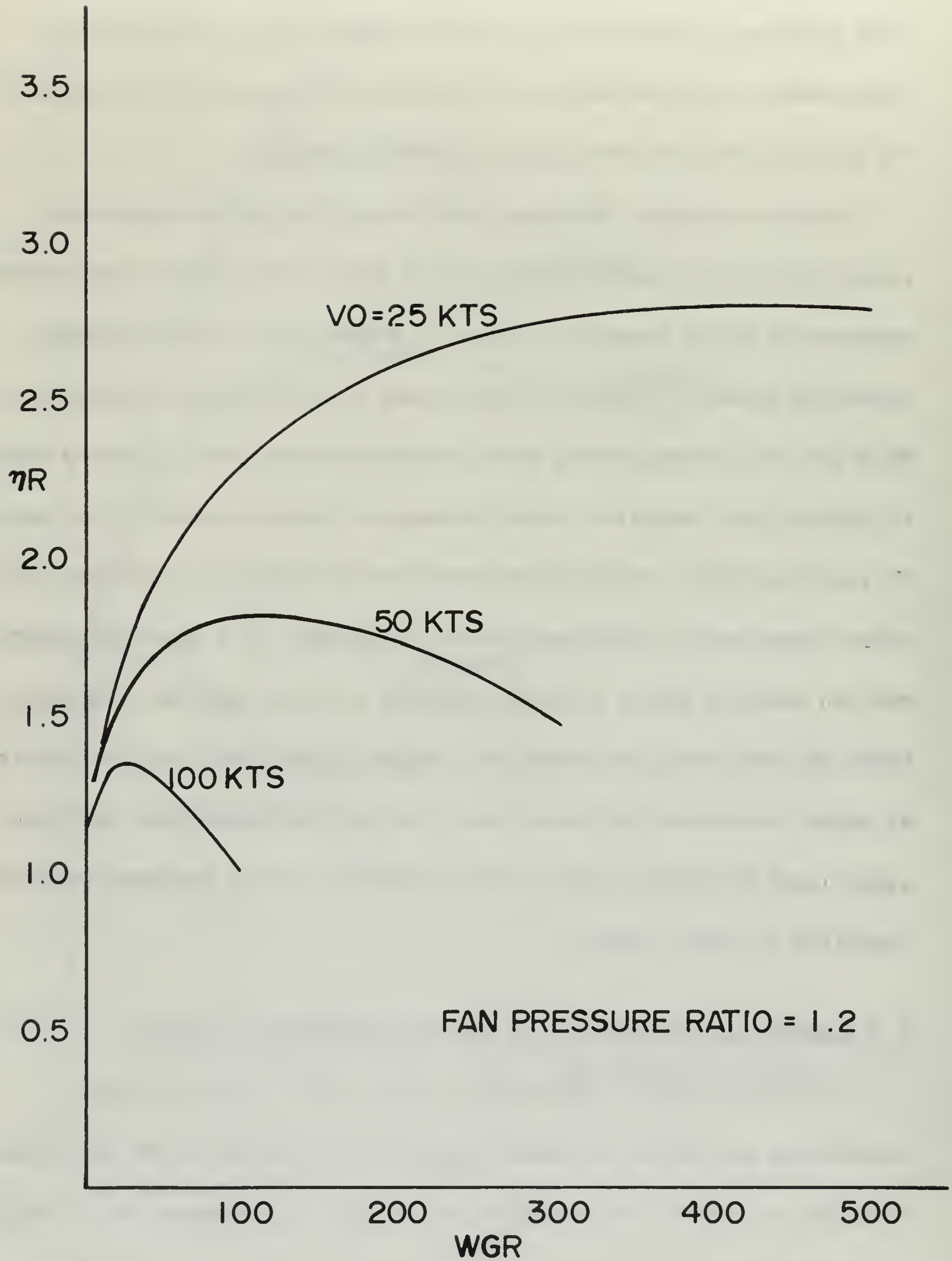


FIGURE 4
EFFICIENCY RATIO VS. WATER TO GAS GENERATOR RATIO

velocity at mixing duct exit (VW8/VA8), and fan nozzle exit (VW9/VA9). Four runs were made holding all but one of the equilibrium parameters fixed at 1.0 and varying the remaining one through its maximum possible range, (Figures 5 through 8). For a slightly more meaningful output the two temperature ratios were varied simultaneously with the velocity ratios held constant (Figure 9) and likewise the velocity ratios varied together with temperature ratios fixed (Figure 10).

Figures 5 and 7 indicate that for all other equilibrium parameters fixed at unity, equilibrium at the mixing duct exit is either detrimental or has no effect on thrust and efficiency ratios. This result was at first thought erroneous but then rationalized as being correct (although unrealistic). Note that for these curves, equilibrium conditions are required at the exit of the fan nozzle. Thus by requiring less equilibrium in the mixing duct, the mixing is being forced to take place in the nozzle, where it occurs isentropically, resulting in higher efficiency and thrust ratios.

The results obtained in Figures 6 and 8 are much more significant as they represent not only physically possible states but, in the case of Figure 6, physically probable ones. Figure 6 shows that thermal equilibrium at the nozzle exit is definitely not desirable. Peak thrust occurs for values of TW9/TS9 between 1.0 and 1.05, which can amount to as much as twenty-five or thirty degrees temperature difference. At greater values of this temperature ratio, thrust falls off again although much more gradually, indicating that a wise operating condition would

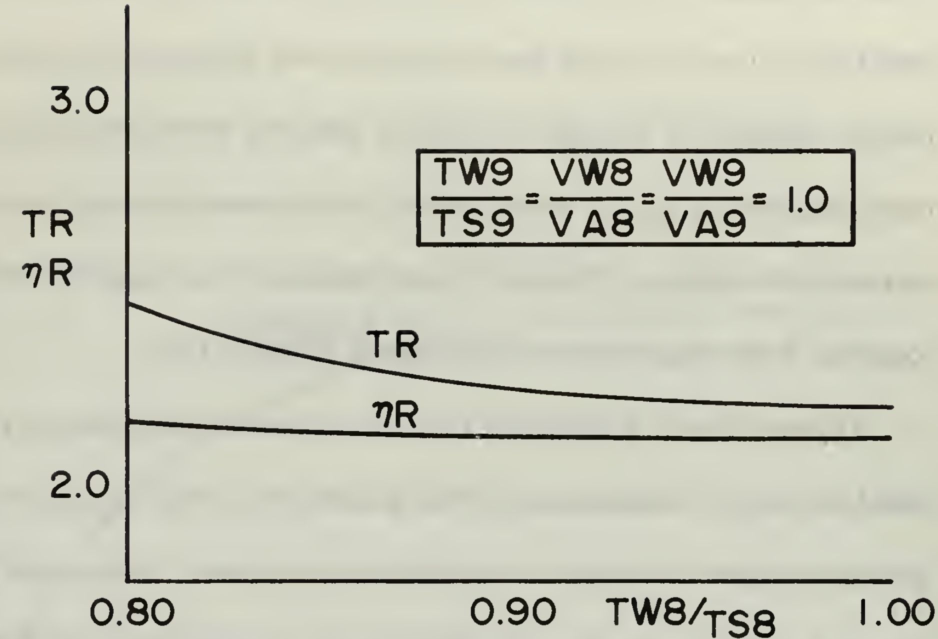


FIGURE 5
THRUST AND EFFICIENCY
RATIO VS. TW8/TS8

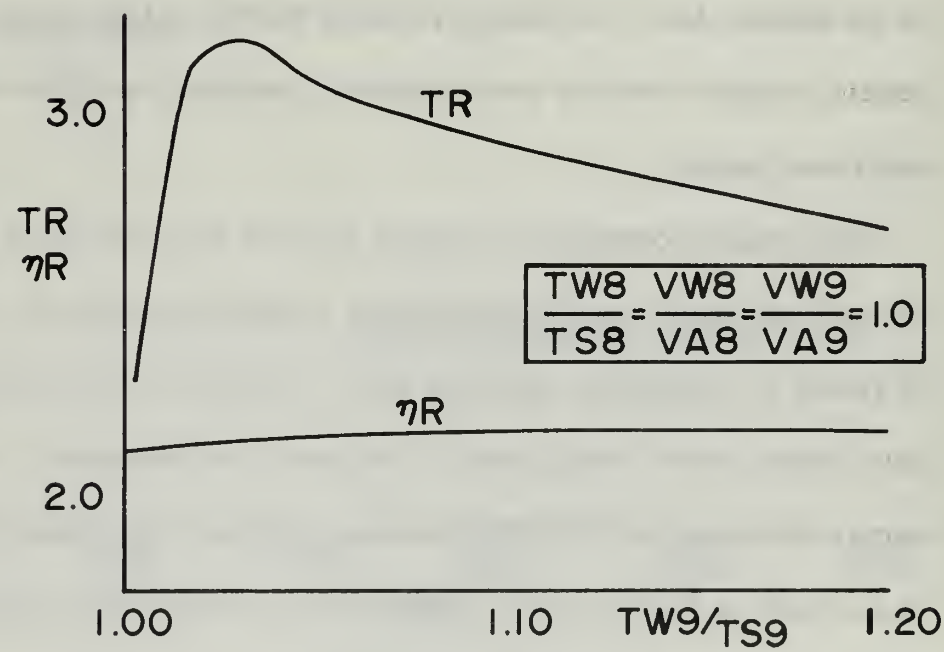


FIGURE 6
THRUST AND EFFICIENCY
RATIO VS. TW9/TS9

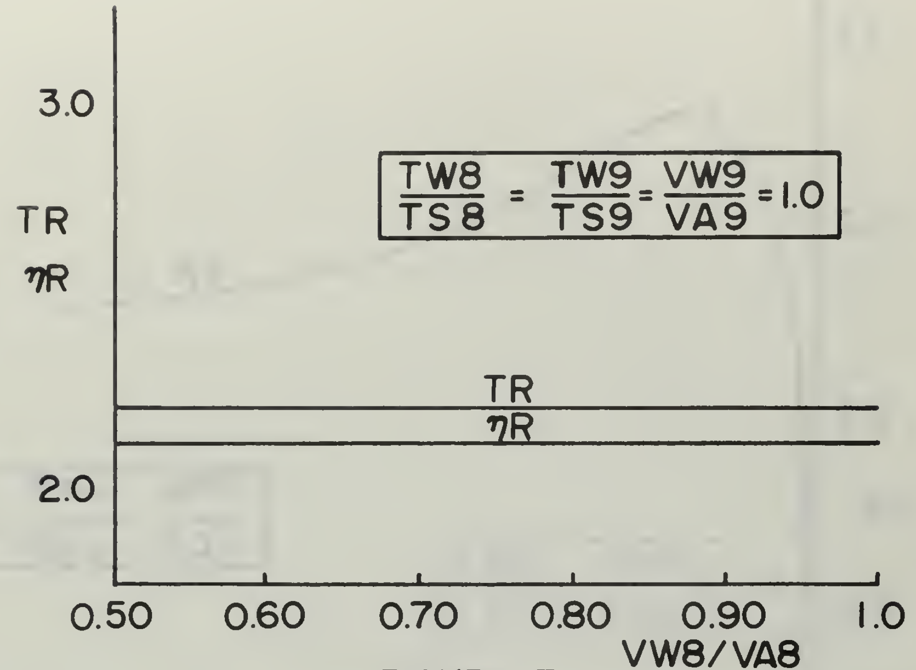


FIGURE 7

THRUST AND EFFICIENCY RATIO VS. VW8/VA8

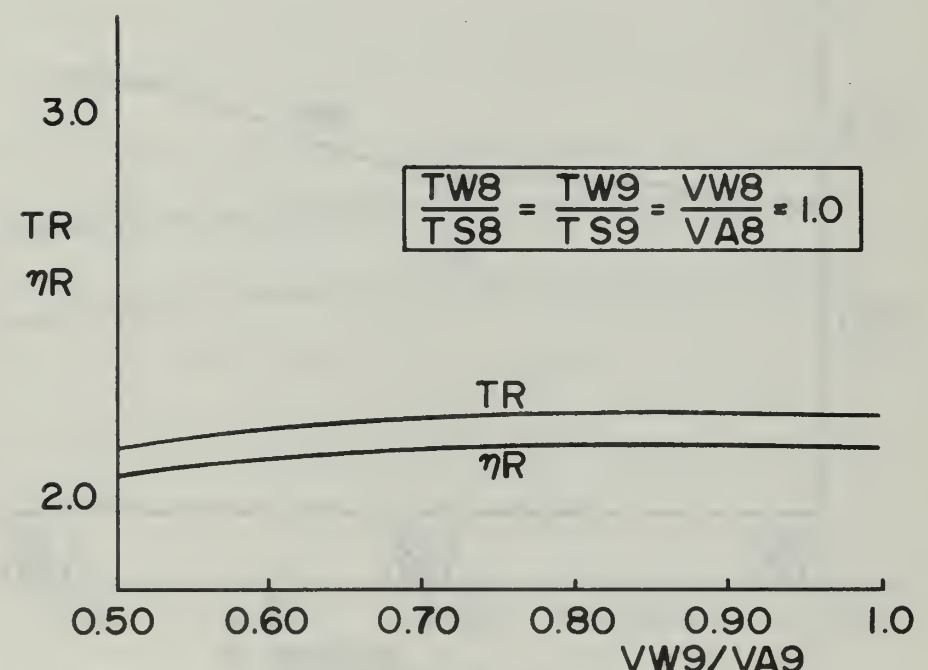


FIGURE 8

THRUST AND EFFICIENCY RATIO VS. VW9/VA9

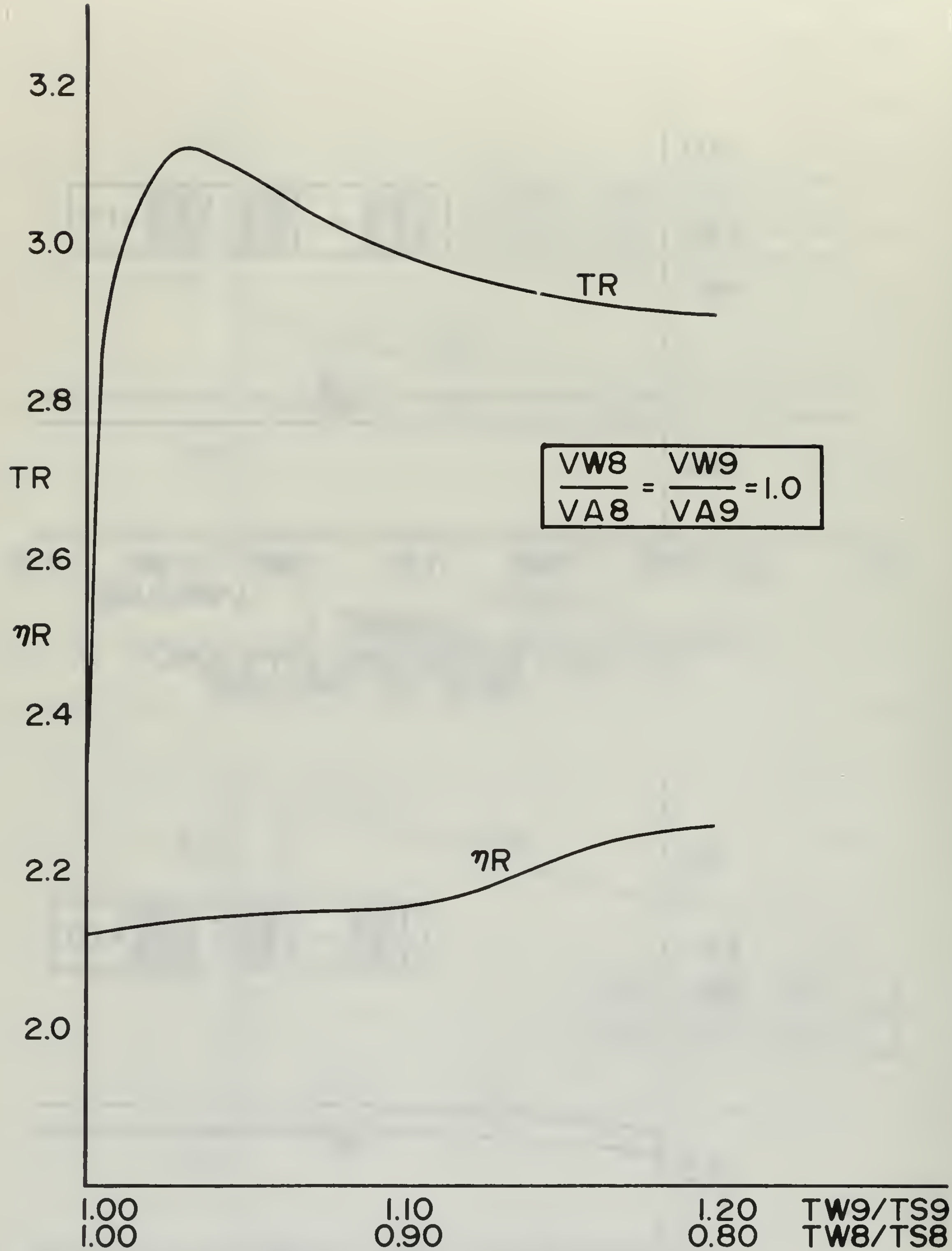


FIGURE 9
THRUST AND EFFICIENCY RATIO VS. TW8/TS8
AND TW9/TS9 VARYING CONCURRENTLY

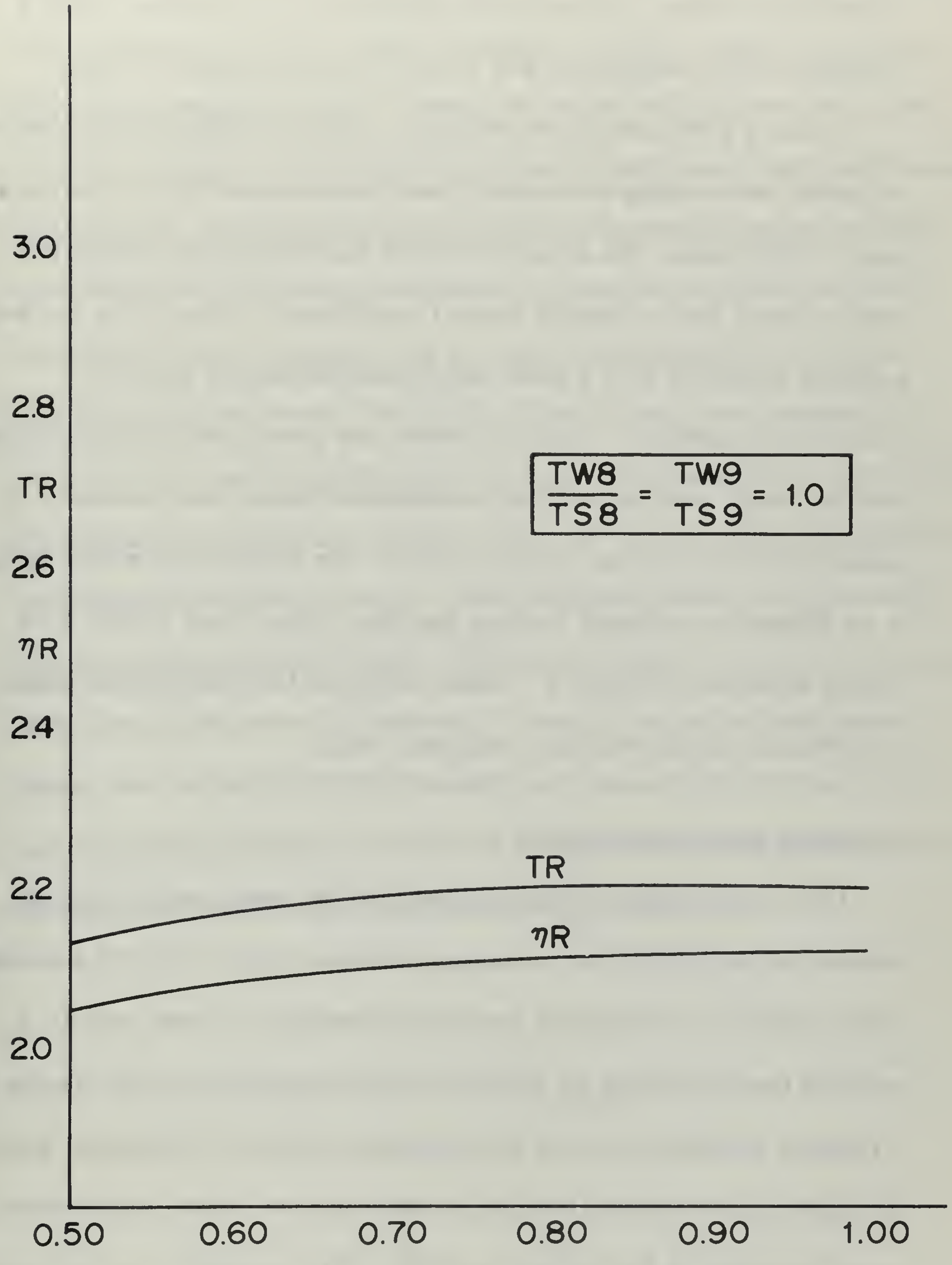


FIGURE 10

THRUST AND EFFICIENCY RATIO VS VW8/VA8 AND VW9/VA9 VARYING CONCURRENTLY

be to the right of the maximum point. Efficiency ratio is not affected to nearly the extent of thrust ratio although it also increases with a divergence from equilibrium and in fact never does begin to peak.

Figure 9 plots thrust and efficiency ratios versus temperature ratio at nozzle exit varying concurrently with temperature ratio at mixing duct exit. In this case, the predominance of the nozzle exit temperature ratio is again felt as perfect thermal equilibrium is seen to be the worst possible condition with a peak value occurring shortly after the equilibrium condition. Figure 10 shows the same type of plot with both velocity ratios varying and both temperature ratios held constant. It reflects the fact that the velocity ratio in the mixing duct makes little or no difference on thrust holding the other ratios fixed in that it is almost identical to Figure 8. Again departure from equilibrium means a decreasing thrust ratio and efficiency ratio.

6.4 Other Results of Analysis

One of the more significant results of the paper was discovered because of initial failures to assume realistic data. Initially a constant water injection velocity was specified regardless of craft speed. It was felt that this could be achieved with proper spray nozzle design and a pumping system to provide the necessary pressure differential when the speed of the vessel through the water did not create enough head to inject the water at the desired velocity. This constant injection velocity specification gave absurdly high values of thrust ratio not believed to be possible. With the new assumption that the injection velocity is a

fraction of the vessel speed (obviating the use of pumps) data were obtained which closely correlate with previous work (2). However, the fact remained that, for a higher injection velocity, values of specific thrust were extremely high. Several TR versus WGR curves for varying injection velocity are presented in Figure 11 with equilibrium parameters, bypass ratio, and fan pressure ratio fixed. It was then postulated that if a pumping system were incorporated to provide the higher injection velocities, such a system could be used in emergencies and/or for important missions when a burst of additional thrust was required. Naturally, the power required to run such a pumping system would reduce the propulsive efficiency, but this would be well offset by the otherwise unobtainable increase in thrust. Note that this would not require more water injection but only higher injection velocities. In effect, it would be a type of sea-borne "afterburner." Such a device in intelligence ships such as the USS PUEBLO would be of unquestioned value for use in emergencies. Perhaps retractable hydrofoils could be incorporated to be used only when on the high thrust mode of operation.

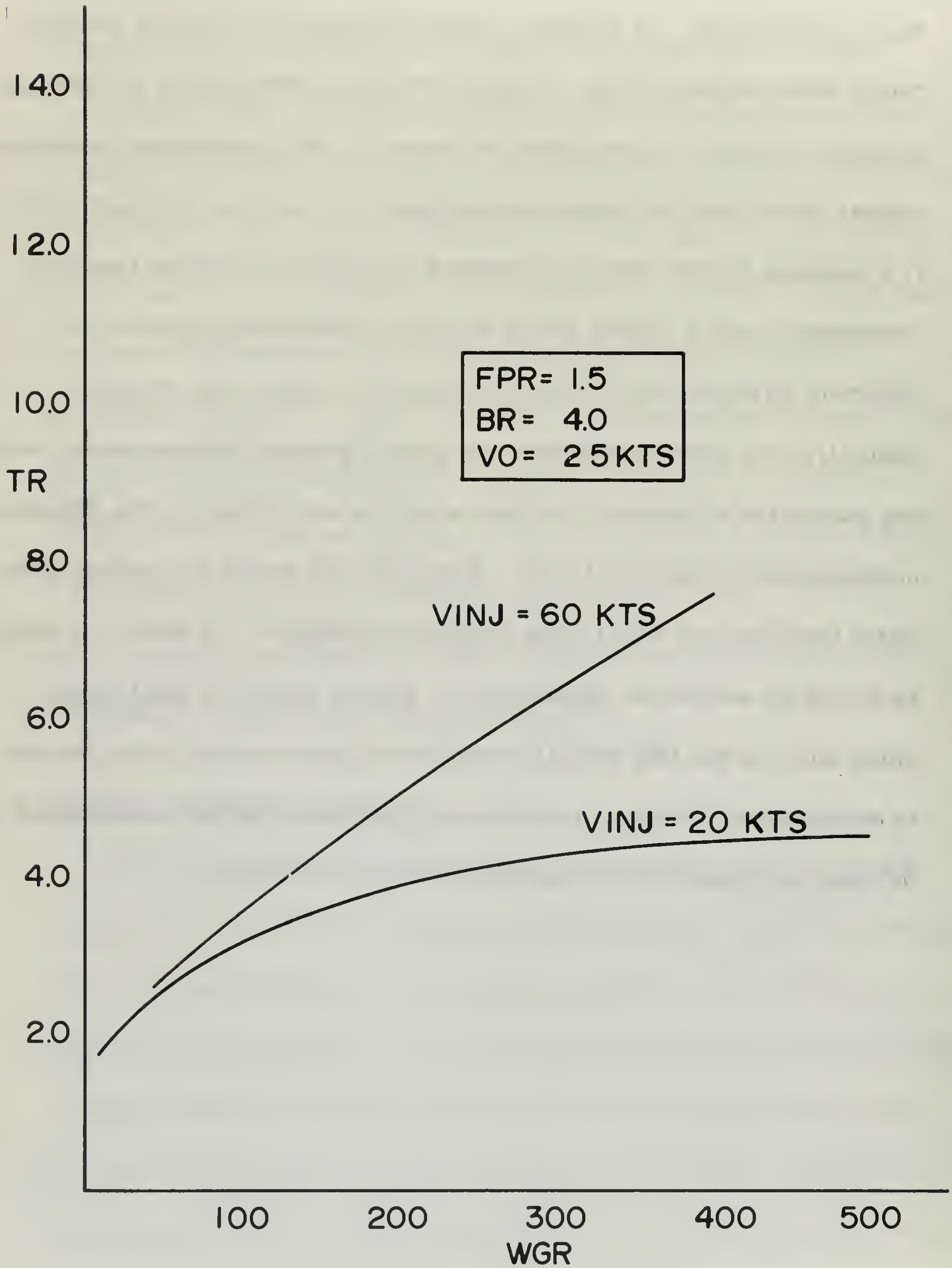


FIGURE 11

THRUST RATIO VS. WATER TO GAS GENERATOR RATIO

CHAPTER VII

CONCLUSIONS AND SUGGESTIONS FOR FURTHER STUDY

7.1 Conclusions

The proposed concept of water injection appears to be a feasible means of increasing thrust and propulsive efficiency. Peak values of thrust ratio and efficiency ratio occur when momentum drag of the injected water predominates over the thrust due to additional mass flow. These peak values occur at lower values of water to gas generator ratio for increasing vessel speed because the momentum drag of the water is proportional to vessel speed.

Peak values for thrust ratios occur slightly before peak values for efficiency ratios since the efficiency is less sensitive to inlet momentum drag of the water.

Static pressure in the mixing duct plays an important role in the slope of the curves and thus determines the effectiveness of the water addition scheme at various ship speeds.

The equilibrium parameter in the mixing process which appears to have significance in affecting system performance is the ratio of water temperature to air temperature at the fan nozzle exit. Peak performance with regard to thrust ratio is obtained when TW9/TS9 is in the range of 1.02 to 1.05. Considerably better values of thrust ratio occur on the side away from equilibrium as opposed to closer to equilibrium. Efficiency ratio continues to improve as TW9/TS9 moves further away from equilibrium.

Normally, injection velocity would be a fraction of the vessel speed determined by how well the ram scoop inlet is designed. If a pumping system is installed such that the water might be injected at a higher velocity, short periods of high thrust could be experienced with a corresponding decrease in propulsive efficiency, such as in an aircraft afterburner.

7.2 Suggestions for Further Study

There is a great deal of further work required before an experimental setup can be constructed; much of this work can be accomplished with this program and modifications to it.

The ambient conditions were fixed throughout this analysis and an investigation into the variations of system performance for different sea water temperatures and air temperatures and pressures could be made. Since vaporization of the water in the mixing sections was of such significance, the effect of relative humidity in the air should be investigated. It should also be possible to choose a friction factor for the mixing duct and through the use of the Fanno flow equations determine the pressure drop in the mixing duct rather than specify it as was done in this analysis. The question of water injection velocity and a pumping system "afterburner" should be investigated with regard to the decreases in efficiency caused by the additional power required to run the pump.

Last and most important, it remains to design and construct an experimental fan section that can investigate the effects of (a) the

equilibrium ratios, (b) static pressure in the mixing duct, and (c) injection velocities of the air and water on thrust and efficiency and to correlate the experimental results with the theoretical values obtained in this program and in this analysis.

LIST OF REFERENCES

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4. Elliott, D. G. "Analysis of the Acceleration of Lithium in a Two-Phase Nozzle," Proceedings of 1963 High Temperature Liquid Metal Heat Transfer Technology Meeting, Oak Ridge, Tennessee, December, 1964, pp. 355-356.

5. Keenan, J. H. and J. G. Keyes. Thermodynamic Properties of Steam, New York: John Wiley and Sons, Inc., 1950.

APPENDIX I

COMPUTER PROGRAM NOMENCLATURE

A1.1 Input Parameters

Card 1:

ETAD	Gas generator diffuser efficiency
ETAC	Compressor efficiency
ETAB	Burner efficiency
ETAT	Turbine efficiency
ETAN	Gas generator nozzle efficiency
ETAFD	Fan duct diffuser efficiency
ETAF	Fan efficiency

Card 2:

DSO	Ambient density (slug/ft^3)
PSO	Ambient pressure (lb/ft^2)
TSO	Ambient temperature (degrees Rankine)
HVF	Heating value of fuel (BTU/lbm)
TREFA	Reference air temperature (492 deg. R)

Card 3:

AMN7	Air injection Mach number
TWO	Sea water temperature (deg. R)
PTR32	Pressure ratio across burner

Card 4:

NVO	Number of vessel speeds
NCPR	Number of compressor pressure ratios
NFPR	Number of fan pressure ratios
NTT	Number of turbine inlet temperatures
NBR	Number of bypass ratios
NWGR	Number of water to gas generator ratios
NMDPR	Number of mixing duct pressure ratios
NMDVR	Number of mixing duct velocity ratios
NMDTR	Number of mixing duct temperature ratios
NFNVR	Number of fan nozzle velocity ratios
NFNTR	Number of fan nozzle temperature ratios

Card 5:

GC	Cool temperature value of ratio of specific heats
GH	Hot temperature value of ratio of specific heats

Card 6:

VO(I)	Values of vessel speed (ft/sec), I = 1,NVO

Card 7:

PTR21(J)	Values of compressor pressure ratio (lb/ft^2), J = 1,NCPR

Card 8:

PTR76(M)	Values of fan pressure ratio (lb/ft^2), M = 1,NFPR

Card 9:

TT3(K)	Values of turbine inlet temperature (deg R), K = 1,NTT

Card 10:

BR(L)	Values of bypass ratio, L = 1,NBR

Card 11:

WGR(N)	Values of water to gas generator ratio, N = 1,NWGR

Card 12:

PSR87(IJ)	Values of mixing duct pressure ratio, IJ = 1,NMDPR

Card 13:

VR8WA(IK)	Values of mixing duct velocity ratio, IK = 1,NMDVR

Card 14:

TSR8WA(IL)	Values of mixing duct temperature ratio, IL = 1,NMDTR

Card 15:

VR9WA(IM)	Values of fan nozzle velocity ratio, IM = 1,NFNVR

Card 16:

TSR9WA(IN)	Values of fan nozzle temperature ratio, IN = 1,NFNTR

AI.2 Output parameters

VA8	Air velocity at mixing duct exit (ft/sec)
VW8	Water velocity at mixing duct exit (ft/sec)
VA9	Air velocity at fan nozzle exit (ft/sec)
VW9	Water velocity at fan nozzle exit (ft/sec)
TS8	Air static temperature at mixing duct exit (^{O}R)
TW8	Water static temperature at mixing duct exit (^{O}R)
TS9	Air static temperature at fan nozzle exit (^{O}R)
TW9	Water static temperature at fan nozzle exit (^{O}R)
STHRUS	Specific thrust (lb thrust/lbm/sec)
AMN5	Gas generator exit Mach number
AMN9	Fan nozzle exit Mach number
ETAPRO	Propulsive efficiency
SFC	Specific fuel consumption (lb fuel/lb thrust-hr)
FAR	Fuel-air ratio (lb fuel/lb air)
X9	Specific humidity at fan nozzle exit (lb vapor/lb dry air)

APPENDIX II

COMPUTER PROGRAM AND SAMPLE OUTPUT


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C
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C
      THOMAS C. KNUDSON
C     WET TURBOFAN
C     SAMPLE DATA RUN
C     20 MARCH, 1968
C
C
      REAL MR
      DIMENSION VO(6),PTR21(10),PTR76(10),TT3(5),BR(10),WGR(10),PSR87(10
     *),VR8WA(10),TSR8WA(10),VR9WA(10),TSR9WA(10)
C
C     STEAM TABLES FUNCTIONS AND DERIVATIVES
C
      HF(XX)= -522.44716 + 1.1719422*XX - .0031882153*XX*XX + .0000019
     *421466*XX**3
      HFG(XX)=1440.548 - 1.1017804*XX + .0010967588*XX*XX - .0000074163
     *358*XX**3
      SF(XX)=-1.6947235 + .0053250001*XX - .0000047499752*XX*XX + .00000
     *000018892757*XX**3
      SFG(XX)=8.812883 - .024424801*XX + .0000283900143*XX*XX - .000000001
     *2441932*XX**3
      DHF(XX)=1.1719422 - .0063764306*XX + .0000058264398*XX*XX
      DHFG(XX)=-1.1017804 + .0021935176*XX - .0000222490074*XX*XX
      DSF(XX)=.0053250001 - .0000094999504*XX + .0000000056678271*XX*XX
      DSFG(XX)=-.024424801 + .0000567800286*XX - .0000000037325796*XX*XX
      READ(5,1)ETAD,ETAC,ETAB,ETAT,ETAN,ETAFD,ETAF
    1 FORMAT(7F5.2)
      READ(5,2)DSO,PSO,TSO,HVF,TREFA
    2 FORMAT(F10.6,4F10.1)
      READ(5,3)AMN7,TWO,PTR32
    3 FORMAT(3F8.2)
      READ(5,4)NVO,NCPR,NFPR,NTT,NBR,NWGR,NMDPR,NMDVR,NMDTR,NENVR,NENTR
    4 FORMAT(11I3)
      READ(5,5)GC,GH
    5 FORMAT(2F9.6)
      READ(5,6)(VO(I),I=1,NVO)
      READ(5,6)(PTR21(J),J=1,NCPR)
      READ(5,6)(PTR76(M),M=1,NFPR)
      READ(5,6)(TT3(K),K=1,NTT)
      READ(5,6)(BR(L),L=1,NBR)
      READ(5,6)(WGR(N),N=1,NWGR)
      READ(5,6)(PSR87(IJ),IJ=1,NMDPR)
      READ(5,6)(VR8WA(IK),IK=1,NMDVR)
      READ(5,6)(TSR8WA(IL),IL=1,NMDTR)
      READ(5,6)(VR9WA(IM),IM=1,NENVR)
      READ(5,6)(TSR9WA(IN),IN=1,NENTR)
    6 FORMAT(10F8.2)
      R=1717.61
      G=32.2
      CJ=778.26
      CPH=GH*R/(GH-1.0)
      CPC=GC*R/(GC-1.0)
      TW7=TWO
      HREFA= CPC*(TSO - TREFA)
```

```
      HREFW=HF(TWO)*CJ*G
      SREFA=0.0
      WRITE(6,50)
   50 FORMAT('1')
      WRITE(6,7)
    7 FORMAT(//////T40,'TURBOFAN ENGINE CYCLE PROGRAM')
      WRITE(6,8)
    8 FORMAT(//T44,'WITH WATER INJECTION')
      WRITE(6,9)
    9 FORMAT(//T47,'ALTITUDE =  0 FT')
      WRITE(6,10)
   10 FORMAT(////T3,'AMBIENT PROPERTIES',T35,'REFERENCE PROPERTIES',T74,
     *'EFFICIENCIES')
      WRITE(6,11)DSO,HREFA,ETAD,PSO,SREFA,ETAC,TSO,HREFW,ETAB,ETAT,ETAN,
     *ETAFD,ETAF
   11 FORMAT(//T3,'DSO = ',F9.6,T21,'SLUG/CU. FT',T35,'HREFA= ',F11.1,T5
     *6,'FT-LB/SLUG',T74,'ETAD = ',F6.2,/,T3,'PSO = ',F9.3,T21,'LB/SQ. F
     *T',T35,'SREFA= ',F11.1,T56,'FT-LB/SLUG-DEG R',T74,'ETAC = ',F6.2,/
     *,T3,'TSO = ',F9.4,T21,'DEG R ',T35,'HREFW =',F11.1,T56,'FT-LB/SLUG
     *-DEG R',T74,'ETAB = ',F6.2,/,T74,'ETAT = ',F6.2,/,T74,'ETAN = ',F6
     *.2,/,T74,'ETAFD = ',F5.2,/,T74,'ETAF = ',F6.2,/,T3,'WATER INJECTIO
     *N SPECIFICATIONS')
      WRITE(6,12)AMN7,TW7
   12 FORMAT(//T3,'AMN7 =',F7.2,/,T3,'VWO =        VO   KNOTS
     *     ',/,T3,'TW7 = ',F7.2,T19,'DEG R')
      DO 36 I=1,NVO
      OV=VO(I)*1.688944
      VWO=OV
      AO=SQRT(GC*R*TSO)
      AMNO=OV/AO
      VW7=0.8 * VWO
C
C     GAS GENERATOR DIFFUSER
C
      PTO  =    PSO*((1.0+((GC-1.0)/2.0)*AMNO*AMNO)**(GC/(GC-1.0)))
      PT1=ETAD *(PTO-PSO) + PSO
      TT1=TSO*(1.0+((GC-1.0)/2.0)*AMNO*AMNO)
      ST1=CPC*ALOG(TT1/TSO)-R*ALOG(PT1/PSO)+SREFA
      HT1=CPC*(TT1-TSO)+HREFA
C
C     FAN DIFFUSER
C
      PT6=ETAFD*(PTO-PSO) + PSO
      TT6=TSO*(1.0+((GC-1.0)/2.0)*AMNO*AMNO)
      ST6=CPC*ALOG(TT6/TSO)-R*ALOG(PT6/PSO)+SREFA
      HT6=CPC*(TT6-TSO)+HREFA
C
C     GAS GENERATOR COMPRESSOR
C
      DO 35 J=1,NCPR
      TT2I=TT1*PTR21(J)**((GC-1.0)/GC)
      DHT21I=CPC*(TT2I-TT1)
      HT2=DHT21I/ETAC + HT1
      TT2=(HT2-HREFA)/CPC + TSO
      PT2=PTR21(J)*PT1
      ST2=CPC*ALOG(TT2/TSO)-R*ALOG(PT2/PSO) + SREFA
C
C     GAS GENERATOR BURNER
C
      DO 34 K=1,NTT
      PT3=PTR32*PT2
      CPB=(CPH + CPC)/2.0
      HT3=CPB*(TT3(K)-TT2) + HT2
      ST3=CPB*ALOG(TT3(K)/TT2) - R*ALOG(PT3/PT2) + SREFA
      FAR=1.0/((ETAB*HVF*G*CJ)/(CPH*(TT3(K)-TT2))-1.0)
C
C     FAN
C
      DO 33 M=1,NFPR
      TT7I=TT6*(PTR76(M)**((GC-1.0)/GC))
      DHT76I=CPC*(TT7I-TT6)
      HT7=DHT76I/ETAF + HT6
      TT7=(HT7-HREFA)/CPC + TSO
```

```
      PT7=PTR76(M)*PT6
      ST7=CPC*ALOG(TT7/TS0)-R*ALOG(PT7/PS0) + SREFA
      WRITE(6,13)
   13 FORMAT(//////,T3,'*********************************************
     ***************************************************************
     *',/,T3,'*****************************************************
     ***********************************************************')
      WV7=0.8*VO(I)
      WRITE(6,14)VO(I),PTR21(J),PTR76(M),TT3(K),WV7
   14 FORMAT(////T10,'VO (KNOTS) IS ',F5.1,/,T10,'COMPRESSOR PRESSURE RA
     *TIO IS ',F5.1,/,T10,'FAN PRESSURE RATIO IS ',F5.1,/,T10,'TURBINE I
     *NLET TEMPERATURE (DEG. R) IS ',F7.1,/,T10,'WATER INJECTION VELOCIT
     *Y (KNOTS) IS ',F5.1,/////)
C
C     GAS GENERATOR TURBINE
C
      DO 32 L=1,NBR
      BY=BR(L)
      CMF=1.0
      FMF=BY
      TMF=CMF + CMF*FAR
      DHT43=(CMF*(HT2-HT1)+FMF*(HT7-HT6))/TMF
      HT4=HT3-DHT43
      DHT43I=DHT43/ETAT
      HT4I=HT3-DHT43I
      TT4I=TT3(K)-(HT3-HT4I)/CPH
      TT4=TT3(K)-(HT3-HT4)/CPH
      PT4I=PT3*((TT4I/TT3(K))**(GH/(GH-1.0)))
      PT4=PT4I
      IF((PT4-PS0).LT.0.0) GO TO 24
      ST4=CPH*ALOG(TT4/TT3(K))-R*ALOG(PT4/PT3) + ST3
C
C     GAS GENERATOR NOZZLE
C
      PS5=PS0
      PS5I=PS0
      TT5I=TT4*((PS5I/PT4)**((GH-1.0)/GH))
      TS5=TT4 - ETAN*(TT4-TT5I)
      TT5=TT4
      ST5=CPH*ALOG(TS5/TT3(K))-R*ALOG(PS5/PT3) + ST3
      VA5=SQRT(2.0*CPH*(TT5-TS5))
      A5=SQRT(GH*R*TS5)
      AMN5=VA5/A5
      STADD=0.0
      IF(AMN5.LE.1.0) GO TO 15
      AMN5=1.0
      VA5=SQRT((2.0*CPH*TT5)/(1.0+2.0*CPH/(GH*R)))
      A5=VA5
      TS5=A5*A5/(GH*R)
      TT5I=(ETAN*TT4-TT4+TS5)/ETAN
      PS5=PT4*(TT5I/TT4)**(GH/(GH-1.0))
      ST5=CPH*ALOG(TS5/TT3(K))-R*ALOG(PS5/PT3) + ST3
      DS5=PS5/(R*TS5)
      STADD=(1.0+FAR)/((1.0+BY)*DS5*VA5)*(PS5-PS0)
C
C     FAN MIXING DUCT
C
   15 DO 31 N=1,NWGR
      MR=WGR(N)/BY
      WMF=WGR(N)*CMF
      TS7=TT7/(1.0+(GC-1.0)/2.0*AMN7*AMN7)
      HS7=(TS7-TS0)*CPC + HREFA
      A7=SQRT(GC*R*TS7)
      VA7=AMN7*A7
      VM7=(VA7+MR*VW7)/(1.0+MR)
      PS7=PT7/(1.0+(GC-1.0)/2.0*AMN7*AMN7)**(GC/(GC-1.0))
      DA7=PS7/(R*TS7)
C
C        MIXING DUCT TEMPERATURE ITERATION
C
      DO 30 IJ=1,NMDPR
      PS8=PSR87(IJ)*PS7
      DW7=1.9378
```

```
      VM8=VM7 + (PS7-PS8)*(1./(1.+MR))*(1./(DA7*VA7)+MR/(DW7*VW7))
      DO 29 IK=1,NMDVR
      VA8=VM8/((1.+MR*VR8WA(IK))/(1.+MR))
      VW8=VR8WA(IK)*VA8
      TS8=530.
      ZA= 3.2437814
      ZB= .00586826
      ZC= .00000001170237 9
      ZD= .0021878462
      DO 28 IL=1,NMDTR
   16 TW8=TSR8WA(IL)*TS8
      ZE= CPC*(TT7-TS8) + MR*(HF(TW7)-HF(TW8))*CJ*G + MR*VW7*VW7/2.
     *  - MR*VW8*VW8/2. - VA8*VA8/2.
      X=(374.11 - (TSR8WA(IL)*TS8 - 492.)*5./9.)
      TK=(273.16 + (TSR8WA(IL)*TS8 - 492.)*5./9.)
      PPV8=  10.**(ALOG10(218.167) - X/TK*((ZA+ZB*X+ZC*X**3)/(1.0+ZD*X))
     *)*14.6959*144.
      Z =PPV8/(PS8-PPV8)*0.622
      PFUN8=ZE/(HFG(TW8)*CJ*G) - Z
      DZE=-CPC - MR*DHF(TW8)*CJ*G
      DT=5./9.*TSR8WA(IL)
      DX=-5./9.*TSR8WA(IL)
      ZM=((1. +ZD*X)*(ZB*DX + 3.*ZC*DX*X**2) - (ZA +ZB*X+ZC*X**3)*(ZD*DX
     *))/(1.+ZD*X)**2
      ZN=(TK*DX - X*DT)/TK**2
      DPPV8= PPV8*(X/TK*ZM + (ZA+ZB*X+ZC*X**3)/(1.+ZD*X)*ZN)
      DZ=((PS8-PPV8)*DPPV8 + PPV8*DPPV8)/(PS8-PPV8)**2*0.622
      DPFUN8=(HFG(TW8)*CJ*G*DZE-ZE*DHFG(TW8)*CJ*G)/(HFG(TW8)*CJ*G)**2-DZ
      TS8=TS8 - PFUN8/DPFUN8
      IF(PFUN8.LE.0.1E-03) GO TO 17
      GO TO 16
   17 TW8=TSR8WA(IL)*TS8
      X=(374.11 - (TSR8WA(IL)*TS8 - 492.)*5./9.)
      TK=(273.16 + (TSR8WA(IL)*TS8 - 492.)*5./9.)
      PPV8=  10.**(ALOG10(218.167) - X/TK*((ZA+ZB*X+ZC*X**3)/(1.0+ZD*X))
     *)*14.6959*144.
      X8=PPV8/(PS8-PPV8)*0.622
C
C     FAN NOZZLE
C
      PS9=PS0
      TS9=520.
      DO 27 IN=1,NFNTR
   18 TW9=TSR9WA(IN)*TS9
      ZQ=(CPC*ALOG(TS8/TS9) - R*ALOG(PS8/PS9) + X8*SFG(TW8)*CJ*G + MR*
     *  (SF(TW8)-SF(TW9))*CJ*G)
      X=(374.11 - (TSR9WA(IN)*TS9 - 492.)*5./9.)
      TK=(273.16 + (TSR9WA(IN)*TS9 - 492.)*5./9.)
      PPV9=  10.**(ALOG10(218.167) - X/TK*((ZA+ZB*X+ZC*X**3)/(1.0+ZD*X))
     *)*14.6959*144.
      ZR=PPV9/(PS9-PPV9)*.622/TSR9WA(IN)
      PFUN9=ZQ/(SFG(TW9)*CJ*G) - ZR
      DZQ=-CPC/TS9 - MR*DSF(TW9)*CJ*G*TSR9WA(IN)
      DT=5./9.*TSR9WA(IN)
      DX=-5./9.*TSR9WA(IN)
      ZM=((1. +ZD*X)*(ZB*DX + 3.*ZC*DX*X**2) - (ZA +ZB*X+ZC*X**3)*(ZD*DX
     *))/(1.+ZD*X)**2
      ZN=(TK*DX - X*DT)/TK**2
      DPPV9= PPV9*(X/TK*ZM + (ZA+ZB*X+ZC*X**3)/(1.+ZD*X)*ZN)
      DZ=((PS9-PPV9)*DPPV9 + PPV9*DPPV9)/(PS9-PPV9)**2*0.622/TSR9WA(IN)
      DPFUN9=((SFG(TW9)*DZQ-ZQ*DSFG(TW9)*TSR9WA(IN))*CJ*G)/(SFG(TW9)*CJ*
     *G)**2 - DZ
      TS9=TS9 - PFUN9/DPFUN9
      IF(PFUN9.LE.0.1E-03) GO TO 19
      GO TO 18
   19 TW9=TSR9WA(IN)*TS9
      X=(374.11 - (TSR9WA(IN)*TS9 - 492.)*5./9.)
      TK=(273.16 + (TSR9WA(IN)*TS9 - 492.)*5./9.)
      PPV9=  10.**(ALOG10(218.167) - X/TK*((ZA+ZB*X+ZC*X**3)/(1.0+ZD*X))
     *)*14.6959*144.
      X9=(PPV9/(PS9-PPV9)*.622)/TSR9WA(IN)
      DO 26 IM=1,NFNVR
      VA9=SQRT((CPC*(TS8-TS9) + X8*HFG(TW8)*CJ*G + MR*HF(TW8)*CJ*G - X9*
```

```
     * HFG(TW9)*CJ*G - MR*HF(TW9)*CJ*G +VA8*VA8/2.*(1.+X8+(MR-X8)*VR8WA(
     *IK)**2))*2./(1. + X9 + (MR-X9)*VR9WA(IM)**2))
      VW9=VR9WA(IM)*VA9
      A9=SQRT(GC*R*TS9)
      AMN9=VA9/A9
C
C     SPECIFIC THRUST AND PROPULSIVE EFFICIENCY CALCULATIONS
C
      STHRUS=(((1.+FAR)/(1.C+BY))*VA5 - (1.0/(1.0+BY))*OV +
     *(BY+BY*X9)/(1.+BY)*VA9 - (BY/(1.+BY))*OV + (WGR(N)-BY*X9)/(1.+BY)*
     * VW9 - (WGR(N)/(1.+BY))*VWO + STADD) /G
      THRUST=STHRUS*(CMF + FMF) * G
      TP=THRUST*OV
      ETAPRO=TP/(TP+TMF/2.0*(VA5-OV)**2 + (FMF+X9*FMF)/2.*(VA9-OV)**2 +
     * (WMF-FMF*X9)/2.*(VW9-VWO)**2)
      FUMF=(TMF - CMF)
      FUWF=FUMF*G
      SFC=(FUWF/THRUST)*3600.0
      WRITE(6,20)
   20 FORMAT(////,T8,'PSR87',T18,'VR8WA',T28,'TSR8WA',T38,'VR9WA',T48,'T
     *SR9WA',T60,'BR',T69,'WGR')
      WRITE(6,21)PSR87(IJ),VR8WA(IK),TSR8WA(IL),VR9WA(IM),TSR9WA(IN),BY,
     *WGR(N)
   21 FORMAT(2X,7F10.2)
      WRITE(6,22)
   22 FORMAT  (/,T8,'VA8',T16,'VW8',T24,'VA9',T32,'VW9',T40,'TS8',T48,'T
     *W8',T56,'TS9',T64,'TW9',T71,'STHRUS',T81,'AMN5',T88,'AMN9',T94,'ET
     *APRO',T102,'SFC',T109,'FAR',T116,'X9')
      WRITE(6,23)VA8,VW8,VA9,VW9,TS8,TW8,TS9,TW9,STHRUS,AMN5,AMN9,ETAPRO
     *,SFC,FAR,X9
   23 FORMAT(4X,8F8.2,F9.2,5F7.3,F7.4)
      GO TO 26
   24 WRITE(6,25)
   25 FORMAT(T5,'TURBINE EXIT PRESSURE IS LOWER THAN ATMOSPHERIC')
   26 CONTINUE
   27 CONTINUE
   28 CONTINUE
   29 CONTINUE
   30 CONTINUE
   31 CONTINUE
   32 CONTINUE
   33 CONTINUE
   34 CONTINUE
   35 CONTINUE
   36 CONTINUE
      RETURN
      END
```

```
                         TURBOFAN ENGINE CYCLE PROGRAM

                            WITH WATER INJECTION

                              ALTITUDE =  0 FT


AMBIENT PROPERTIES              REFERENCE PROPERTIES                     EFFICIENCIES

DSO =  0.002378   SLUG/CU. FT   HREFA=     168325.8   FT-LB/SLUG          ETAD =    0.95
PSO =  2116.000   LB/SQ. FT     SREFA=          0.0   FT-LB/SLUG-DEG R    ETAC =    0.90
TSO =  520.0000   DEG R         HREFW =    703221.7   FT-LB/SLUG-DEG R    ETAB =    1.00
                                                                          ETAT =    0.85
                                                                          ETAN =    0.98
                                                                          ETAFD =   0.95
WATER INJECTION SPECIFICATIONS                                            ETAF =    0.90

AMN7 =    0.10
VWC =       VO    KNOTS
TW7 =   520.00    DEG R



****************************************************************************************************
****************************************************************************************************


     VO (KNOTS) IS  25.0
     COMPRESSOR PRESSURE RATIO IS  13.8
     FAN PRESSURE RATIO IS   1.5
     TURBINE INLET TEMPERATURE (DEG. R) IS  2500.0
     WATER INJECTION VELOCITY (KNOTS) IS  20.0



   PSR87     VR8WA     TSR8WA    VR9WA     TSR9WA      BR       WGR
    1.00      1.00      1.00      1.00      1.00      4.00     10.00

   VA8     VW8     VA9     VW9     TS8     TW8     TS9     TW9     STHRUS    AMN5    AMN9   ETAPRO  SFC     FAR     X9
   58.16   58.16   499.85  499.85  521.64  521.64  514.82  514.82   51.63    1.000   0.449  0.102   0.275   0.020   0.3091


   PSR87     VR8WA     TSR8WA    VR9WA     TSR9WA      BR       WGR
    1.00     -1.00      1.00      1.00      1.00      4.00     20.00

   VA8     VW8     VA9     VW9     TS8     TW8     TS9     TW9     STHRUS    AMN5    AMN9   ETAPRO  SFC     FAR     X9
   48.00   48.00   366.58  366.58  520.86  520.86  517.34  517.34   60.19    1.000   0.329  0.124   0.236   0.020   0.3100
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13. ABSTRACT

This paper presents a theoretical investigation of a water-augmented turbofan engine, one in which large quantities of sea water are injected into the fan duct section. Results indicate that up to three or four times dry thrust and propulsive efficiency are obtained depending on vessel speed, fan pressure ratio, and amount of water injected. Optimum water injection velocity is investigated. Deviations from thermal and dynamic equilibrium in the mixing processes are investigated with respect to their effect on overall performance.

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